Development of a New Method for Calculating Viscosity at High Pressures

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Abstract

Fluids released by a subducting plate 100 km below the Earth's surface cause melting in the overlying mantle, leading to arc volcanism, such as that found in the Andes mountains. The viscosity of the released fluid is a first-order constraint on the transport of material from the plate to the mantle. Accurate determination of fluid viscosity at appropriate pressures (>30 kbar or 3 GPa) and temperatures (~800C) is hampered by the geometry of high-pressure devices. The goal of this research is to construct a new method for quantifying the viscosity of water at pressures similar to those in subduction zones. By observing the Brownian motion of polystyrene spheres suspended in fluid contained in a diamond anvil cell (DAC), the viscosity of the fluid can be calculated. Preliminary results yield an accuracy within half an order of magnitude of published values. Future experimental plans involve measuring the viscosity of water up to 3GPa and 800C. To further mimic conditions of subduction zones, dissolved hydrated minerals such as chlorite will be added to the water.

Geologic Background

Arc volcanism can be attributed to 'flux melting' of the mantle wedge caused by release of H_2O during dehydration reactions involving hydrated minerals at depth. The water released from dehydration reactions saturates the surrounding material, thereby lowering its melting point. Most of the H_2O is released from serpentine and chlorite [*Iwamori*, 1997].

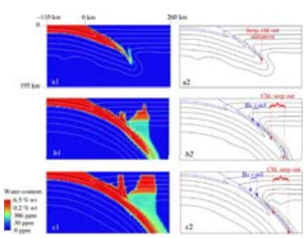


Fig. 1 The subducting slab contains oceanic crust which begins to dehydrate at ~65 km, thus causing flux melting of the mantle wedge and crust. Large columns of the mantle are immediately hydrated since asthenospheric rocks can only dissolve ppm of water [*Arcay et al*, 2005].

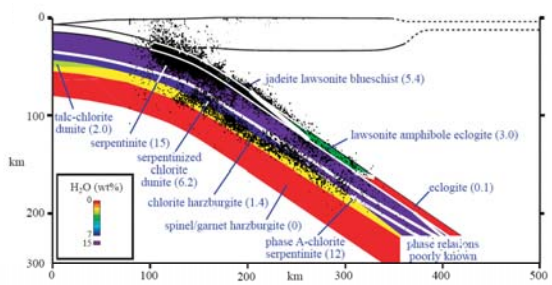


Fig. 2 Metamorphic facies in the Honshu subduction zone were modeled by Hacker et al (2003). The two facies that contain the most water are serpentinite and phase A-chlorite serpentinite. Dehydration of subducted slabs has also been associated with deep-focus seismic activity [*Meade and Jeanloz*, 1991; *Raleigh and Paterson*, 1965]. The fractures produced by these earthquakes become conduits for the transport of water.

Brownian Motion

Brownian motion is the random movement of particles in a gas or liquid medium due to the interaction with the molecular forces of the fluid. Einstein described the movement as a diffusion process and equated the mean-square displacement to the diffusion coefficient to derive an equation for Avogadro's number [*Einstein*, 1926]. The equation for MSD as a function of time is:

$$\langle x^2 \rangle = \frac{4kT}{6\pi a\eta}t \qquad \textbf{(1)}$$

k is Boltzmann's constant
T is temperature in Kelvin
a is the radius of the particle
η is the viscosity of the fluid

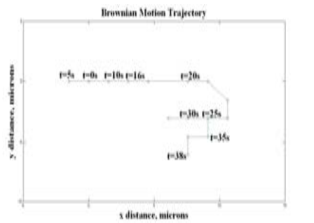
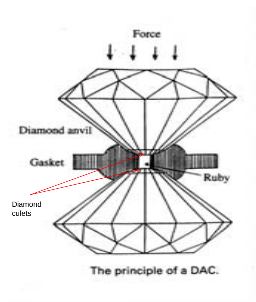


Fig. 3 Vector position of a polystyrene sphere suspended in distilled water within a diamond anvil cell at STP. Position of the particle was generated by a particle-tracking velocimetry program written in MATLAB.

Method

Two samples were prepared for analysis. 3.0 µm polystyrene spheres were added to distilled water and a 0.9780*m* sucrose-distilled water solution. The sucrose solution was used to verify an increase in viscosity. Each solution was loaded into a diamond anvil cell with a small Cr-doped ruby chip for pressure measurement. The loaded DAC was placed under a microscope with a digital camera connected to the ocular of the microscope. Brownian motion of the polystyrene spheres was videotaped for 38-40 seconds. The videos were then run through a particle tracking velocimetry (PTV) program written in MATLAB. The program tracks the position of the particle at every frame and assigns a distance value proportional to the length of a pixel. By summing the squares of the vector distance at each time step, the MSD is calculated.



(www.earth.northwestern.edu/research/jacobsen)

Fig. 4 Gaskets (stainless steel) are indented and drilled to form a strong sample chamber. The gasket is situated between two diamonds and loaded with water. Pressure is induced by applying a moderate force across the culets of the two diamonds.

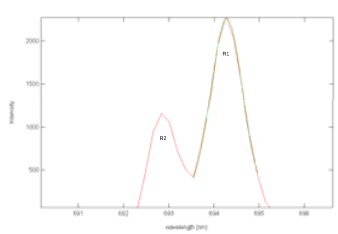


Fig. 5 Representative graph of peaks obtained by ruby fluorescence. Two distinct peaks, R1 and R2, are emitted when Cr-doped ruby is excited by a 488nm Ar-ion laser. The peaks shift to higher wavelengths with increasing pressure.

Results and Discussion

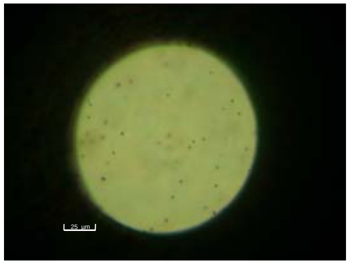


Fig. 6 DAC loaded with water-polystyrene sphere solution as seen under a petrographic microscope.

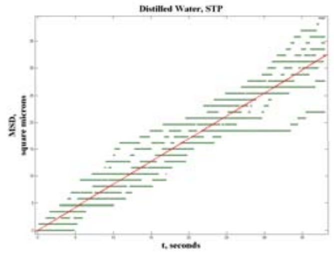


Fig. 7 Mean square displacement versus time of 8 particles suspended in water at STP. The slope of the best-fit line represents the diffusion coefficient, which in turn is used to determine the viscosity of the fluid.

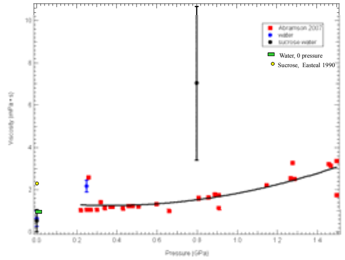


Fig. 8 Viscosity versus pressure of experimental data compared with published data. Data were collected at 21 C. There are no published values for sucrose water solution at elevated pressures for comparison.

The values of water viscosity are within a factor of 2 of the published data. Values for the sucrose sucrose solution are within half of an order of magnitude for the sucrose solution. Data in which the cursor in the PTV program lost track of the particle were discarded. Ruby fluorescence pressure measurements may not be as precise at such low pressures since the error associated with the method can be greater than the range of pressure ranges that are being measured.

Conclusions

- •The resulting viscosities obtained from the experiments are within an acceptable range of published values to continue experimentation
- • Better accuracy in data analysis can be obtained by tracking more particles.
- •The pressure measurements using ruby fluorescence might not be precise enough for these purposes. These problems could be solved by using a hydrothermal diamond anvil cell. The temperature is regulated so the pressure can be determined by following the phase diagram of water.
- •Density of the particles in suspension plays an important role. If there are too many particles, they interact with each other and will lead to inaccurate viscosity measurements. Too little particles, and the bulk of them settle before pressure measurements can be made.
- •Brownian motion combined with the DAC may be a useful method for calculating viscosity at conditions related to subduction zones.

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